The First Muon Collider - 125 GeV Higgs Factory?

David Neuffer[a]

[a]*Fermilab, PO Box 500, Batavia IL 60510 USA*

Abstract.

Because muons connect directly to a standard-model Higgs particle in s-channel production, a muon collider would be an ideal device for precision measurement of the mass and width of a Higgs-like particle, and for further exploration of its production and decay properties. The LHC has seen evidence for a 125 GeV Higgs particle, and a muon collider at that energy could be constructed. Parameters of a high-precision muon collider are presented and the necessary components and performance are described. Extension to a higher-energy higher-luminosity device is also discussed.

Keywords: Higgs, muons, colliders.
PACS: 14.80.Bn, 14.60.Bf, 29.20.db, 29.27.Hg

INTRODUCTION

Recently the CERN ATLAS and CMS collaborations have presented evidence for a "standard-model" Higgs particle at ~125GeV. (see Figure 1) This evidence is at the ~4+σ level, and is not quite certain, but the result is consistent with the standard model and all other Higgs masses are largely excluded. The Higgs candidate has an appearance cross-section consistent with a minimal standard-model Higgs. This minimal Higgs has a small production cross-section with a very narrow width. As discussed in Barger et al.,[1] a minimal Higgs could be produced in the s-channel in a muon collider. ($\mu^+ + \mu^- \rightarrow H_0$) The possibility of producing and studying the standard model Higgs at the ~100 GeV energy was explored by the Muon Collaboration in 1996-2003[2, 3] and most of that discussion remains valid in the present context. In the present paper, we review those studies and extend them, following more recent studies in muon production, cooling, and acceleration within the Muon Collider and Neutrino Factory Collaboration (MCNFC). Scenarios for a Higgs-energy μ^+-μ^- Collider are developed. Muon spin precession can accurately calibrate the mass and width, and the nearby high cross-section Z_0 resonance can be exploited for development and debugging of the facility. Extension of an initial facility toward higher energy and luminosity is discussed.

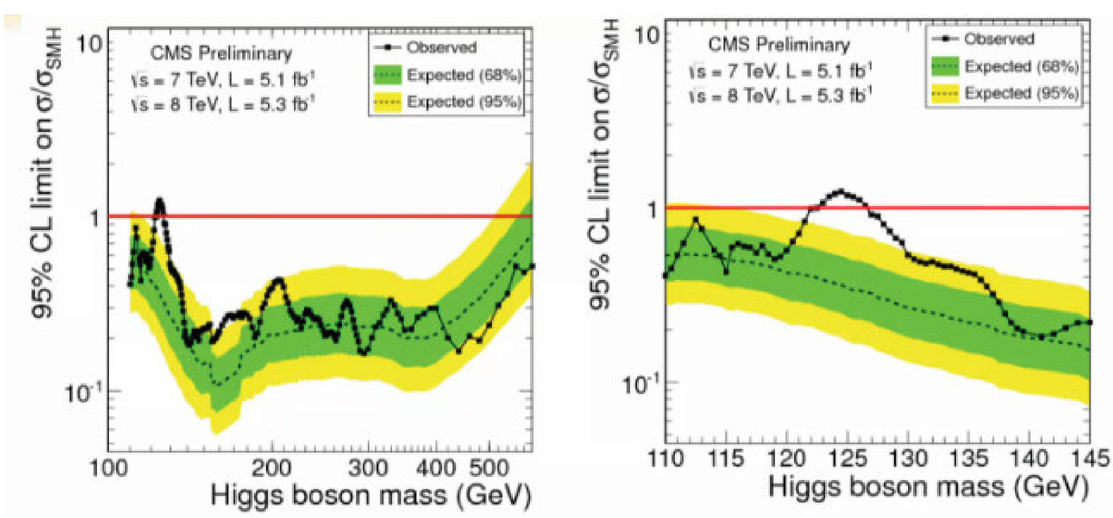

FIGURE 1. This displays some initial CMS data supporting the existence of a "Higgs-like" particle at 125GeV.

OVERVIEW OF A 125 GeV HIGGS μ^+-μ^- COLLIDER

At 125 GeV, the standard-model Higgs is a narrow resonance with a width of ~3 MeV, and the cross-section for production from μ^+-μ^- $\rightarrow H_0$ is ~50pb. This is relatively small, but is $(m_\mu/m_e)^2$ larger than for an e^+-e^- collider, and a luminosity of $L = 10^{31}$ cm^{-2}/s would provide ~5000 H_0 / 10^7 s operational "year". A scan over the Higgs mass with a small-δE muon collider would resolve that mass and width to high accuracy, much higher than any alternative H_0 studies. The initial difficulty will be in isolating the H_0 and a scan over a larger energy spread will be needed. Fig. 2A shows a simulation of such a scan, requiring ~10^7 s at $L=10^{31}$. The standard H_0 will decay to b-$\bar{b}$ quarks predominantly, which will aid in its separation from the production background of ~80 pb.

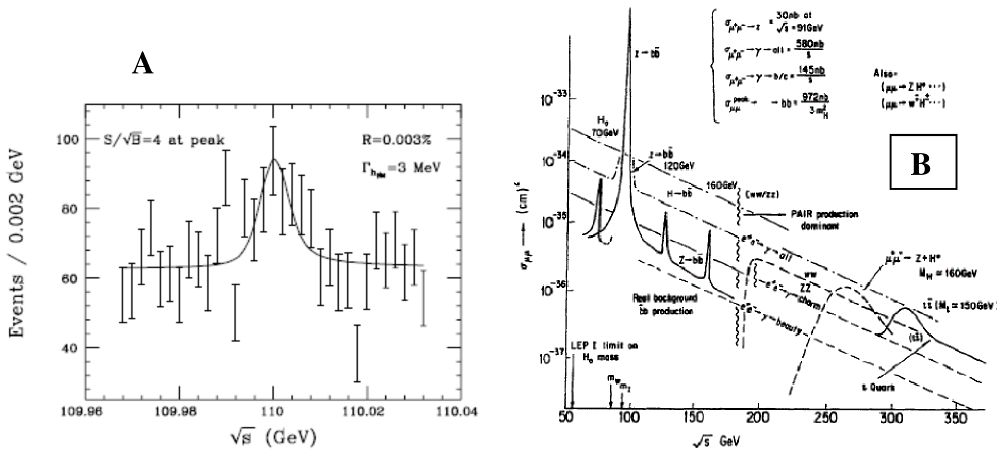

FIGURE 2. **A**:This displays a simulated 110GeV Higgs scan at a μ^+-μ^- Collider (from ref. 2). **B**: An overview of $\sigma_{\mu\mu}\rightarrow$?? at E = 50 to 350 GeV, showing the Z peak, possible H results, and other known effects. (from ref. 4)

An e^+-e^- Collider cannot produce H_0 directly but can produce it in association with a Z_0 (e^+-$e^- \rightarrow Z_0 + H_o$) at higher energy and low-cross-section (~0.2pb at 250 GeV, with ~20pb background). A much higher luminosity (L~10^{34}) is needed and the precision of energy measurement and direct width measurement will be much degraded. Associated production in a muon Collider will also occur at a similar cross-section. The direct production by μ^+-μ^- would be greatly preferable since it enables precision measurement and requires a luminosity of "only" 10^{31}, but it does require small-δE beam (δE < 10 MeV with <3MeV preferred).

An artistic impression of a muon collider is presented in Fig. 3. It consists of a source of high-intensity short proton pulses, a production target with collection of secondary π's, a decay transport, a bunching and cooling channel to capture and cool μ's from π decay into intense bunches, an accelerator that takes the μ+ and μ^- bunches to a collider ring for full-energy collision in an interaction region inside a Detector. Refs. 2 and 3 presented low-energy collider scenarios and we have adapted their versions, following more recent research, to obtain collider parameters presented in Table 1. The components are discussed below.

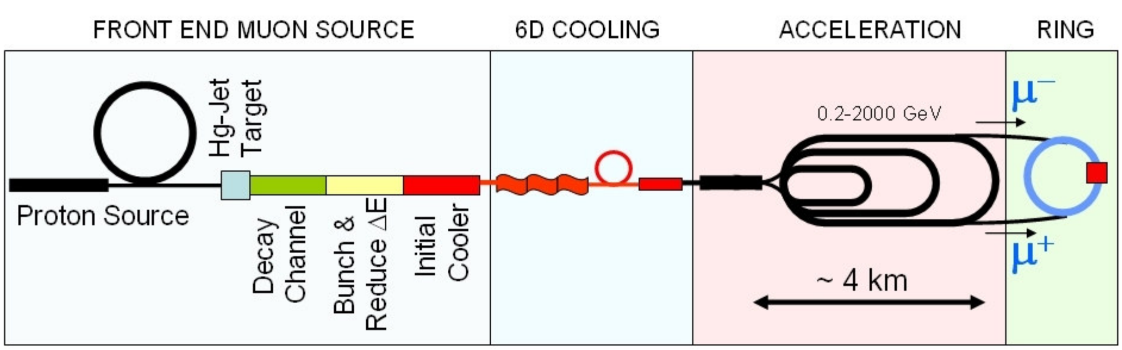

FIGURE 3. An overview of a μ^+-μ^- Collider Facility, extending up to 2×2 TeV. (from ref. 3)

Proton Source, Target and μ Capture Scenarios

A number of proton source variants have been considered. Our version is based on the Project X 8 GeV linac, upgraded to provide 4MW in 15 Hz pulsed mode.[5] In our initial version H^- beam from a 15 Hz pulse is accumulated over many turns in a storage ring (using charge-exchange injection to H^+) and bunched into 4 short bunches, that are extracted one at a time to the Front End production target, forming the 60 Hz cycle used in Table 1.

These bunches are targeted onto a production target producing large number of π's, that will decay into μ's. Following the neutrino-factory front-end design [6, 7] this could be a Hg-jet target immersed in a high field solenoid for maximum π-capture, tapering to a lower field transport for $\pi \rightarrow \mu$ decay. ~300—200 MHz rf cavities form the μ's into trains of μ^+ and μ^- bunches, which are phase-energy rotated into equal energy bunches, at which an ionization cooling transport (solenoids +rf + absorbers) initiates the cooling needed for the collider. This Front End is ~150m long.

Collider parameter	**Small δE 125 GeV Collider**
Energy/beam E_μ	62.5 GeV
Luminosity L	10^{31}
Proton Energy, Power E_p	8GeV, 4MW
N_p/bunch, frequency	5×10^{13}, 60 Hz
N_μ/ bunch	1.5×10^{12}
Normalized emittances: ε_L, ε_T	0.002, 0.0005m
IR focus: β*	0.1m
Beam size σ_{IR}	0.3mm
Collider circumference C	350m
Energy width δE	2 MeV
Bunch length σ_{bunch}	10cm
Tune shift $\delta\nu_{beam\text{-}beam}$	0.0003
Higgs/yr (est.)	4000

Cooling Scenario and constraints

The small δE requirement of the Collider implies that the beam must be cooled to minimal longitudinal emittances. The baseline cooling scenario for a Collider starts with bunch trains from the front End and cools them both transversely and longitudinally in a sequence of spiral or helical channels, merges the bunches and further cools the beam toward minimal transverse emittances. (see Fig. 4) For the 125 GeV Collider the cooling scenario would be truncated at minimal longitudinal emittance, where ε_L = ~0.001m and the transverse emittance ε_t is ~0.0005m. ε_t could be further reduced to ~0.0002m.

At slightly inferior values, ε_L = ~0.002m, an rms bunch length of 10cm would have an energy width of ~2 MeV, which would be small enough for precision exploration of the Higgs. The β* must be ≥ the bunch length, because of the hourglass effect. A larger energy width (or smaller ε_L) would enable smaller β* and therefore larger luminosity. (A larger δE, L collider could be useful in the initial scan for the H_0.)

Acceleration and Collider Ring

Following neutrino factory designs, muon bunches can be accelerated in a linac and a sequence of recirculating linacs (RLA) to 62.5 GeV, where the μ^+ and μ^- bunches would be inserted into a fixed-field collider ring. A scenario with a 1.8 GeV linac and 2 4.5 pass RLA's (to 7.2 and 62.5 GeV) is a possible extrapolation of the neutrino factory designs, and is used in our initial scenario. [7]

Lattices for Higgs colliders at 50 and 55 GeV/beam have been previously developed and can be adapted and updated for the 62.5 GeV/beam collider ring.[9] These lattices have been designed to operate in a small δE mode to maximize resonance production (β^* = 14cm) or a larger δE mode with higher luminosity (β^* = 4cm) that may be better adapted to the energy search for the H_o resonance. A racetrack lattice was designed with a low-β IR in one straight section and a collimation insertion in the opposite straight. Collimation of beam halo with absorber plates at 5σ was designed. The lattice should be restudied; it could be desirable to have 2 IR's, placed at the opposite straights. Beam-beam tune shifts are modest. Beam stability issues of a 50×50 GeV collider ring were explored by Ng[10]; that study should be updated to the present scenario.

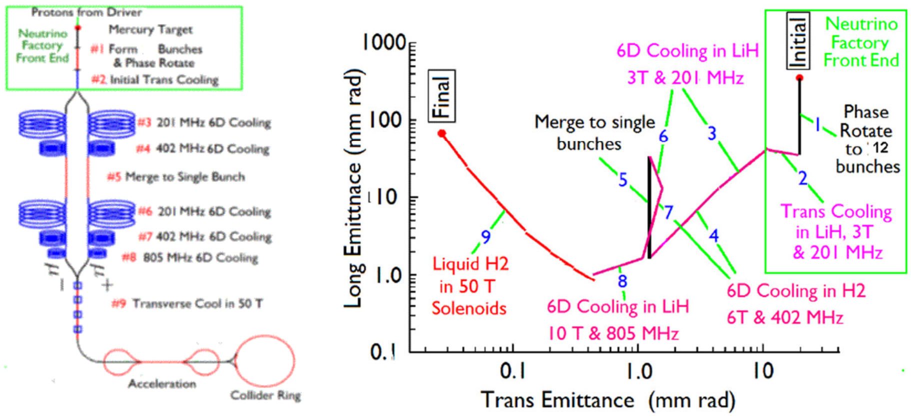

Figure 4: Overview of a cooling scenario for a high energy collider. (from ref. 8) Figure A shows an overview of the cooling beam transports, and B shows the progress of transverse and longitudinal emittances through the system. For the Higgs Collider the scenario could be followed to minimal longitudinal emittance, which would occur after stage 7 or 8, without the final stages for cooling to small transverse emittance. Stages 3, 4, 6, 7, 8 correspond to 6-D cooling in a spiral alternating-solenoid transport with wedge absorbers and high-gradient rf at 201, 402, or 804 MHz.

Energy Determination by Spin Tracking

Raja and Tollestrup noted that the energy of the beams can be measured to high accuracy by tracking the precession of the decay electron energies.[11] While stored, the muons continuously decay following $\mu \rightarrow e + \nu_\mu + \bar{\nu}_e$, at ~10^6 decays per m, and the electrons and positrons from the decay have a mean energy dependent on the polarization of the muons. That polarization $\hat{P}$ will precess as the beam rotates around the ring and that precession will modulate the mean energy of decay electrons, and therefore the signal from a calorimeter capturing those decays. In the present capture scenario the μ beams are created with a small polarization (~10—20% from a bias toward capture of forward $\pi \rightarrow \mu$ decays) and that polarization should be substantially maintained through the cooling and acceleration systems. The mean energy from decay electrons is: $\langle E(t) \rangle = \left\langle N e^{-\alpha t} \left(\frac{7}{20} E_\mu \left(1 + \frac{\beta}{7} \hat{P} \cos(\omega t + \phi) \right) \right) \right\rangle$ where N is the initial number of μ's, E_μ is the μ energy, α is the decay parameter, β = v/c, P is the polarization, ϕ is a phase, t is time in turn numbers and

$\omega = 2\pi\gamma \left(\frac{g-2}{2} \right) \cong 2\pi\, 0.7$ is the precession frequency that depends on the muon beam energy. A calorimeter capturing a significant number of decay electrons will have a signal modulated by that precession frequency, and since it is a frequency it can be measured to very high accuracy, implying an energy measurement to high accuracy, possibly to the ~10^{-6} level (corresponding to 60 keV error).

Collider at the Z_0: "Training Wheels" for the Higgs Factory

Initial operation of a collider at a small-δE, small-σ H_0 appears quite daunting, particularly since initial luminosities will be less than desired. However the 125 GeV Higgs is quite close to the 91.2 GeV Z_0, where the production cross section is almost 1000 times larger (~30nb), and a luminosity of only ~10^{27} would see Z_0 production events. (see Fig. 2B) We propose to initially operate and debug the facility at that collision energy. The large cross section nearly guarantees the existence of non-background events in early operation and the difficult task of separating signal from backgrounds will be initiated at relatively easy parameters. The energy measurement technique would be initiated and debugged at a well-known value, and a sweep of a small δE Collider over the 2.5 GeV width of the Z_0 would provide valuable information on the Collider operation and nontrivial information on Z_0 properties. When high-luminosity is established, backgrounds and errors are understood, and energy calibration is developed, the acceleration and storage ring will be increased from 45.6 to 62.5 GeV, and the scan for the Higgs will begin.

Although the Z_0 is well known, the comparison of μ^+-$\mu^- \rightarrow Z_0$ with e^+-e^- will be of some interest, and the spin precession measurement of the energy and width could even be more accurate than existing measurements (which are at $\delta E \sim 2$ MeV).

Luminosity and Energy Upgrades

A successful Collider could be optimized and improved toward higher luminosity. More cooling could reduce transverse emittance and/or bunch length. Stronger focusing could reduce β^* by a factor of 2—4. For higher luminosity, the 4 bunches from the accumulator can be combined to hit the target at the same time, reducing the cycling frequency from 60 Hz, but increasing the μ's /cycle by as much as a factor of 4. These and other upgrades could increase L to $\sim 10^{32}$, but not much larger in a low-energy small-δE mode, unless the proton source power is greatly increased.

While the LHC has not yet identified any other new physics states, any new physics could be explored by higher-energy μ^+-μ^- Colliders. Supersymmetry models predict more Higgs states beyond the low-mass H_0, and these would be produced at higher cross-sections and could be studied in a higher-energy collider. Acceleration to higher energies may be more readily obtained in a very-rapid-cycling synchrotron scenario.

At higher energies the resonance widths are larger, and the beams could therefore be cooled transversely by another order of magnitude, with some increase in longitudinal emittance (see fig. 4). That and adiabatic damping would increase luminosity to $> 10^{34}$ for a multi-TeV Collider.

Summary

We have discussed potential parameters for a 125 GeV μ^+-μ^- Collider, suitable for observation and precision measurement of the Higgs particle at that energy. Such a collider requires an initial luminosity of $\sim 10^{31}\text{cm}^{-2}\text{s}^{-1}$, and would be expandable toward higher energy and luminosity. The collider would not be easy or very inexpensive. It requires a MW+ scale proton source, a high-acceptance $\pi \rightarrow \mu$ collection channel and a sequence of ionization cooling systems. Initial operation would require searching for a narrow-width, relatively small-cross section resonance, although that search could be preceded by the much easier search and study of μ^+-$\mu^- \rightarrow Z_0$ at 91 GeV, at which techniques needed for the more difficult H_0 search and measurement can be established.

ACKNOWLEDGMENTS

We particularly acknowledge the continuing interest and contributions of David Cline in a Higgs muon collider. We also acknowledge helpful discussions with V. Shiltsev, S. Nagaitsev, R. Palmer, M. Palmer and many other members of the MAP collaboration.

REFERENCES

1. V. Barger, M. S. Berger, J. F. Gunion and T. Han, *Physics Reports* **286**, 1-51 (1997).
2. C. Ankenbrandt et al., *Physical Review STAB* **2**, 081001 (1999).
3. M. M. Alsharo'a et al., *Physical Review STAB* **6**, 081001 (2003).
4. D. Cline, "Physics Potential of a few hundred GeV μ^+-μ^- Collider" in *Physics Potential and Development of μ^+-μ^- Colliders*, edited by D. B. Cline, AIP Conf. Proc. 352, A. I. P., Woodbury, NY, 1996, pp. 3-6.
5. Y. Alexahin and D. Neuffer, "Design of Accumulator and Compressor Rings for the Project-X Based Proton Driver", Proc. IPAC2012 (2012).
6. D. Neuffer et al., "IDR Neutrino Factory Front End and Variations", paper TUPPD006, Proc. IPAC2012 (2012).
7. M. Appollonio et al., "Accelerator Concept for Future Neutrino Facilities", RAL-TR-2007-23, *JINST* **4** P07001 (2009).
8. R. Palmer et al., "Scheme for Ionization Cooling for a Muon Collider", Proc. NuFACT08, 10th Int. Conf. on Neutrino Factories, Super Beams, and Beta Beams, Valencia, Spain, July 2008.
9. C. Johnstone, W. Wan and A. Garren, "Lattice design for a 50 on 50 GeV Muon Collider", Proc. 1999 PAC, New York, p. 3065 (1999).
10. K-Y. Ng, *Physical Review STAB* **2**, 091001 (1999).
11. R. Raja and A. Tollestrup, *Physical Review D* **58**, 013005 (1998).